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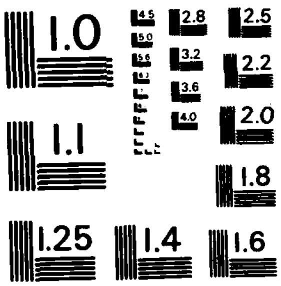

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ROYAL SIGNALS & RADAR ESTABLISHMENT

SERVO SYSTEM FOR THE ATHERMALISATION OF A GERMANIUM LENS

Authors: I C Carmichael
J D Roberts

PROCUREMENT EXECUTIVE,
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ROYAL SIGNALS AND RADAR ESTABLISHMENT

Memorandum 3527

Title: SERVO SYSTEM FOR THE ATHERMALISATION OF A GERMANIUM LENS

Authors: I C Carmichael and J D Roberts

Date: November 1982

SUMMARY

This memorandum describes a simple electronically controlled servo system that was developed to athermalise the germanium lens of a radiometer operating in the infra-red waveband. The system athermalisation was demonstrated, with the result that the radiometer signal was held to within 95% of maximum for a $\pm$ 20°C lens temperature change; this compares with a signal loss of over 90% with no athermalisation.

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RSRE MEMORANDUM

SERVO SYSTEM FOR THE ATHERMALISATION OF A GERMANIUM LENS

I C Carmichael and J D Roberts

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1 INTRODUCTION

Germanium is a material which is frequently used in infra-red optics, but it does have the disadvantage of a refractive index that changes significantly with temperature[1]. The consequence of this disadvantage when applied to a system is a reduction in performance. In the case of an imaging system the performance may be restored by a focus adjustment. The situation considered here is that of a staring radiometer, where in general no image is present. For this type of system if an optimum performance is to be maintained over a wide temeprature range it is necessary to use athermalised optics. To achieve system athermalisation a simple electronic servo was developed to move the detector to compensate for a change in lens temperature. This memorandum describes the servo system and reports some results obtained using it.

2 DESIGN REQUIREMENTS FOR A SERVO FOCUS SYSTEM

Previous experiments (1) on an IR radiometer which was not achromatised in the (3-5 μm) waveband showed that its performance was seriously degraded by changes in the lens temperature in both the (8-12)μm and (3-5)μm wavebands. Data from these experiments form the basis for the athermalisation servo system described below.

2.1 Temperature Resolution and Longitudinal Focal Shift

Following Rayleigh's criterion an optical system is considered to be 'sensibly perfect' if the wavefront aberration is $\leq \lambda/4$. Maréchal[2] equated this criterion to a 20% loss in the peak intensity of the diffraction image of a point source at infinity. From ref (1) the magnitude of temperature change to introduced a 20% loss in peak intensity may be calculated using

$$|\Delta T| = \lambda\gamma/2f(NA)^2$$

where γ is the waveband average temperature defocus coefficient, f is the lens focal length and (NA) is the lens numerical aperture. For the radiometer considered in this paper

$$|\Delta T|_{(8-12)\ \mu m} = 1.7^{\circ}C$$

and

$$|\Delta T|_{(3-5)\ \mu m} = 0.7^{\circ}C$$

Experiments with the radiometer system[1] showed that the change in focal position with temperature ($\partial f/\partial T$) of a germanium lens was linear over the range -25°C to +40°C in the (3-5) μm and the (8-12) μm wavebands. The gradients ($\partial f/\partial T$) were measured to be

$$\frac{\partial f}{\partial T}_{(8-12)\ \mu m} = -50.95\ \mu m/K^{\circ}$$

and

$$\frac{\partial f}{\partial T}_{(3-5)\ \mu m} = -60.45\ \mu m/K^{\circ}$$

To accommodate the different gradients two gain settings are required in the servo amplifier.

Combining $(\partial f/\partial T)$ with $|\Delta T|$ the magnitude of longitudinal focal shift (ΔZ) necessary to produce a 20% loss in peak signal (for an achromatised optic) is

$$\Delta Z\ (8\text{-}12)\ \mu m = 87\ \mu m$$

and

$$\Delta Z\ (3\text{-}5)\ \mu m = 43\ \mu m$$

in the respective wavebands. If the servo system is to correct for these focal shifts the detector position has to be controlled and measured to the order of 50 μm and hence from $|\Delta T|$ the lens temperature must be measured to $\pm$ 0.5°C.

In the case considered here, that is for a non-achromatised germanium optic a focal resolution of 50 μm is sufficient in the (3-5) μm waveband. The limiting resolution for this system is given by the longitudinal focal broadening due to dispersion in the lens material.

2.2 Object Range and Waveband Control

To achieve focus over the range 200 metres to infinity it is necessary to include a control potentiometer calibrated in metres, however it is not necessary to vary the amplifier gain $(\partial f/\partial T)$ as a function of object distance, see Appendix A.

To enable a two waveband operation capability a DC shift, corresponding to a focal shift of 2.74 mm is included in the servo. This shift is necessary because of dispersion within the lens.

3 SERVO FOCUS SYSTEM DESIGN

As indicated in the section on design requirements it was necessary to be able to measure the temperature of the lens accurate to $\pm$ 0.5°C. Also to be able to adjust and measure the focus position to 50 μm. A linearised platinum resistance thermometer of a commercial design was used to measure the temperature of the lens. The focus position was adjusted with a motor driven micrometer where a DC permanent magnet motor drives the thimble of the micrometer. The position was measured on a precision linear potentiometer.

The thermometer has an output voltage slope of 4.4 mV/°C. The linear potentiometer is fed with a stable reference voltage of 10 volts and has an output slope of 8 mV per 50 μm.

The object range setting control is a potentiometer which is fed with a stable reference voltage of 2.45 volts. This control has its scale calibrated in metres from 200 metres to infinity.

3.1 Servo Amplifier

The servo amplifier consists of four distinct areas which are designed to combine and amplify the inputs from the temperature sensor (thermometer) position sensor (potentiometer) and range control (potentiometer), these are shown schematically in Figure 1.

Block 1

This is a buffer stage with an input resistance of 2 megohms. This value of resistance only changes the linearity of the 10 kilo ohm position sensor potentiometer by 0.5% over is full range. The component values are chosen to compensate for bias current and voltage changes which occur with circuit temperature changes.

Block 2

This is an amplifier with a nominal gain of times two and is used to amplify the temperature information. The waveband change characteristics are incorporated in this amplifier. Two parameters need to be changed for a change in waveband. The first is a shift in the basic focus position, this is achieved by altering the DC working point of the amplifier to produce the required focus position for each waveband. The other is a change of $\partial f/\partial T$ between wavebands. Here the gain of the amplifier is adjusted to one of two values, near its nominal value of times two, by switching the value of the feedback resistor.

Block 3 and 4

This third stage combines the amplified and DC shifted temperature signal with the buffered voltage from the linear potentiometer.

A third voltage is fed in at this point which is derived from the calibrated object range control potentiometer. The voltage output of this third stage is the error which is zero when the focus position is correct for the demanded object range, lens temperature and waveband. A fourth stage amplifiers, this error and drives the DC motor which in turn rotates the micrometric thimble and adjusts the focus position to the correct setting. The 100 Hz power line ripple is attenuatedby 10 dbs at 25 Hz by low pass filter which is incorporated in this mixing stage. In order to assist the inherent viscous friction damping in the motor drive, phase advance damping with a time constant of about ¼ sec is included in the position feedback part of the servo loop. The component values and resistor voltages are chosen to reduce the effect of a bias current and voltage changes caused by circuit temperature changes to about a ¼ of the final accuracy required by the focus position criterion. The voltage sources for the object range control precision linear potentiometer and waveband change are derived from reference voltage supplies which a stability of 0.01% in the temperature range in which the circuit is to operate.

4 EXPERIMENTS

The experiments were of two types. The first was to check the accuracy and performance of the mechanical and electrical aspects of the servo system. The second was to check the effectiveness of the athermalisation servo in total.

4.1 Mechanical and Electrical Performance

In order to check the mechanical and electrical performance it was necessary to be able to measure the mechanical movement of the focusing mount and also to simulate temperature changes for the thermometer. Focus position was measured by measuring the voltage from the linear poteniometer on a digital voltmeter and as indicated previously it had a relationship of 8 mV/50 μm. In order to simulate temperature changes the platinum

resistance sensor element of the thermometer, which had a nominal value of 90 ohms, was replaced by a variable resistor. The value of this resistor could be adjusted to obtain the required temperature reading on the digital display of the thermometer.

The relationship between temperature and focus position could now be obtained.

The gain and offsets were set up, to the values, as indicated in section 2 for the two wavebands. The linearity was measured to be within $0.1^{\circ}C$ over the simulated temperature range of $+40^{\circ}C$ to $-20^{\circ}C$. This characteristic was obtained by plotting the position of the focus head against lens temperature. The mean slope of the characteristic was accurate to within $0.1^{\circ}C$ of the design requirements, but individual points on the characters could deviate by $\pm 0.5^{\circ}C$ from the mean. This $\pm 0.5^{\circ}C$ is equivalent to a focus position error of about 50 μm. This is within the design requirements as explained in section 2-1.

4.2 Effectiveness of the Athermalisation Servo System

The radiometer used for this experiment is shown schematically in Figure 2. The radiometer system was essentially comprised of a lens mounted on one side of a metal casting, a fold mirror mounted at 45° to the optical axis, and a detector positioned vertically above the mirror. To achieve the best focus the detector was moved vertically above the mirror along the optical axis. The optic used was a very well corrected and anti-reflection coated single element polycrystalline germanium meniscus lens, with a clear aperture of 180 mm and a numerical aperture of 0.243. Energy incident from a modulated thermal source was focused on to a cooled photo-conductive Cd Hg Te detector of linear dimensions 115 x 125 μm. The signal from the detector was amplified and displayed on an oscilloscope. System athermalisation was included as described in section 3.

4.2.1 Radiometer performance with and without athermalisation in the (8-12) μm and in the (3-5) μm wavebands

The percentage of the maximum signal with and without athermalisation is shown in figure 3 for the (8-12) μm waveband; and with athermalisation in Figure 4 for the (3-5) μm waveband. The maximum signal is defined to be the peak signal following a manual focus adjustment at any given lens temperature. Figures 3 and 4 show the effectiveness of the servo controlled athermalisation technique over a wide temperature difference. The slow initial loss of signal in Figure 3 for the case of no athermalisation occurs because for a small lens temperature change the image point spread (For $T = 0$ the image point spread = Airy Disc) falls on the sensitive area of the detector. The Airy disc diameter of the first minimum contour for 10 μm radiation is 50 μm, compared to the detector diameter of 115 μm.

4.2.2 Range potentiometer calibration and longitudinal waveband shift

The position of best focus was calculated as a function of object-range using a finite ray-trace, the results are shown in Figure 5, also shown are the measured positions of image distance against range. The results derived experimentally were used to calibrate the range control potentiometer. The good agreement between the theory and the

experiment in predicting the rate of change of focal position with object range show that it is possible to make a good initial choice of control potentiometer for calibration.

The experiment to measure the focal shift between wavebands yielded the result that the (8-12) μm focus was 2.74 mm further from the lens than the (3-5) μm focal position.

5 CONCLUSIONS

This paper has reported the success of a simple servo controlled electronic system to athermalise the lens of a thermal radiometer. Here success is defined to be a radiometer signal held to better than 95% of maximum following a lens temperature change of $\pm$ 20^{o}C, compared to a signal loss of over 90% with no athermalisation. Although the servo system has been designed to operate with one particular germanium lens this technique may be applied to other lens systems and materials. The majority of materials currently in use in infra-red optics(1) exhibit a much smaller optical degradation for a given temperature change than does germanium. Hence a system of the type described in this paper is sufficiently accurate to be applied to these other materials.

6 ACKNOWLEDGEMENTS

Assistance with the experimental measurements - G Aston, F Mansfield and R W Nowell. Use of raytrace programmes - J Warner.

REFERENCES

1 RSRE Memorandum 3398. The influence of the temperature coefficient of refractive index on a thermal imager. I C Carmichael 1981.

2 Principles of Optics, 3rd Edition, M Born and E Wolf, page 468.

NOMENCLATURE

$\frac{\partial n}{\partial t}$	temperature coefficient of refractive index
$\frac{\partial f}{\partial T}$	shift in focus with temperature
dZ	minimum resolvable movement
λ	wavelength
f	focal length
ℓ	object distance
ℓ'	image distance
r_1	lens radius of curvature, 1st surface
r_2	lens radius of curvature, 2nd surface
to	lens centre thickness
n	lens refractive index
NA	lens numerical aperture
γ	material temperature coefficient of refractive index, waveband average

APPENDIX A

A1 THE EFFECT UPON $\partial f/\partial T$ AS A FUNCTION OF OBJECT RANGE

A1.1 The Shift in Image Position as a Function of a Change in Focal Length

Using the relationship (Ai) between the focal length (f), the object-distance (ℓ), and the image-distance (ℓ') for a lens

$$\frac{1}{f} = \frac{1}{\ell'} - \frac{1}{\ell} \qquad \text{A(i)}$$

the change in image position as a function of a change in focal length may be determined. Re-arranging A(i) and differentiating ℓ' with respect to f, yields

$$d\ell' = \frac{\ell^2}{(\ell+f)^2}\, df \qquad \text{A(ii)}$$

From A(i)

$$\frac{\ell^2}{(\ell+f)^2} = \left(\frac{\ell'}{f}\right)^2$$

therefore substituting into A(ii) gives

$$d\ell' = \left(\frac{\ell'}{f}\right)^2 df \qquad \text{A(iii)}$$

A1.2 Focal Shift with Temperature via Refractive Index

The shift in focus df resulting from a change in refractive index with temperature of a singlet lens is given in Ref (1).

$$df = -\frac{f^2}{r_1 r_2}\left\{ r_2 - r_1 + to\left(1 - \frac{1}{n^2}\right)\right\}\frac{\partial n}{\partial t} \qquad \text{A(iv)}$$

A1.3 Focal shift with Temperature via Refractive Index as a Function of Object Distance

Substituting A(iii) into A(iv) and rearranging gives

$$d\ell' = -\frac{\ell'}{r_1 r_2}\left\{ r_2 - r_1 + to\left(1 - \frac{1}{n^2}\right)\right\}\frac{\partial n}{\partial t} \qquad \text{A(v)}$$

which for an infinite object-distance reduces to A(iv), the simple change in focal length with temperature.

The error in applying A(iv) to non-infinite objects may be evaluated using A(ii) to determine ($d\ell'$) the corrected value of df. The error in df will be greatest at the minimum object distance, which in this case is 200 metres. Substituting for f and ℓ in A(ii), where $f = 357 \times 10^{-3}$ m and $\ell = 200$ m, gives

$$d\ell' = 0.996\ df$$

This yields an 0.4% error in $\partial f/\partial T$ for a 200 metre range which is considered as being negligible.

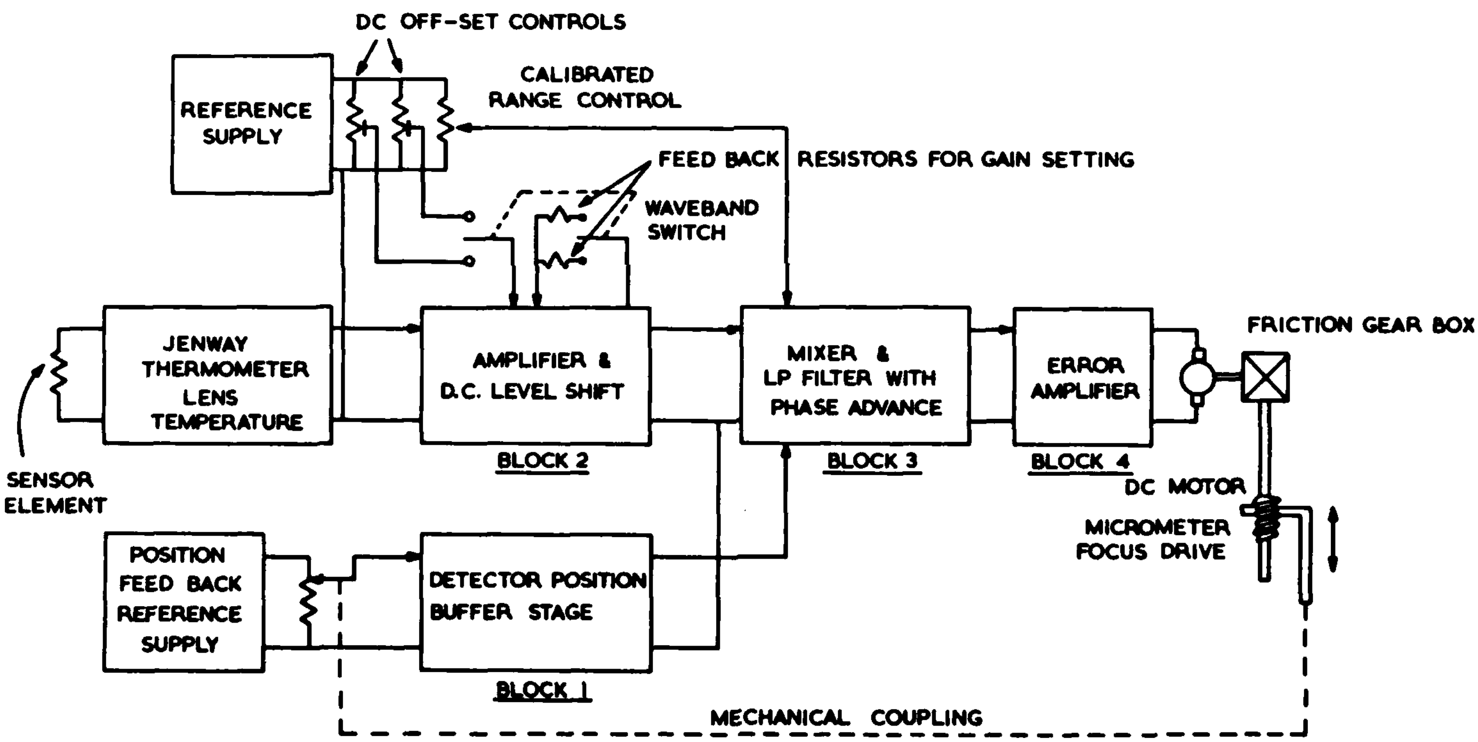

FIG.1 AUTOMATIC FOCUSING SYSTEM

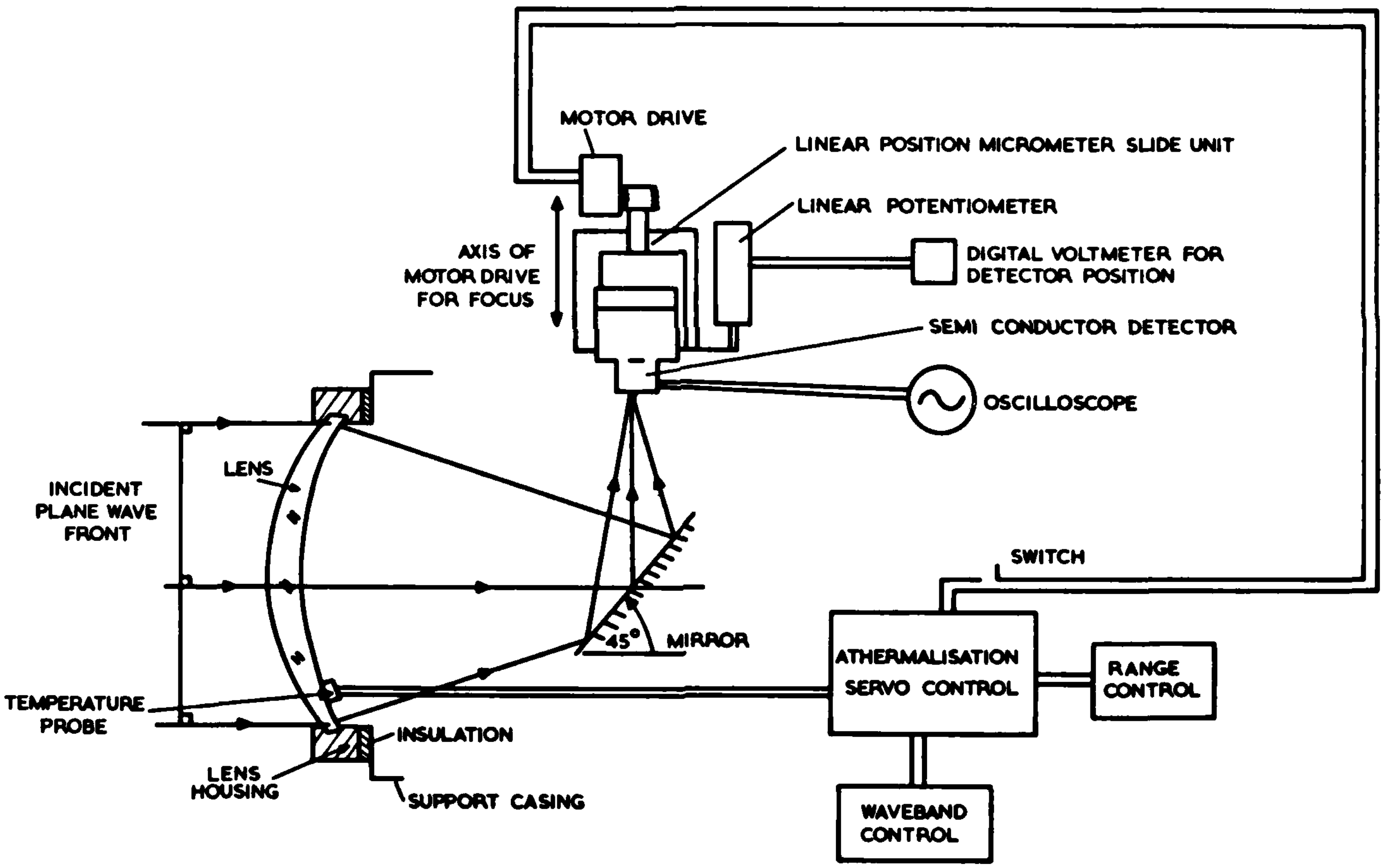

FIG. 2 ATHERMALISATION EXPERIMENT

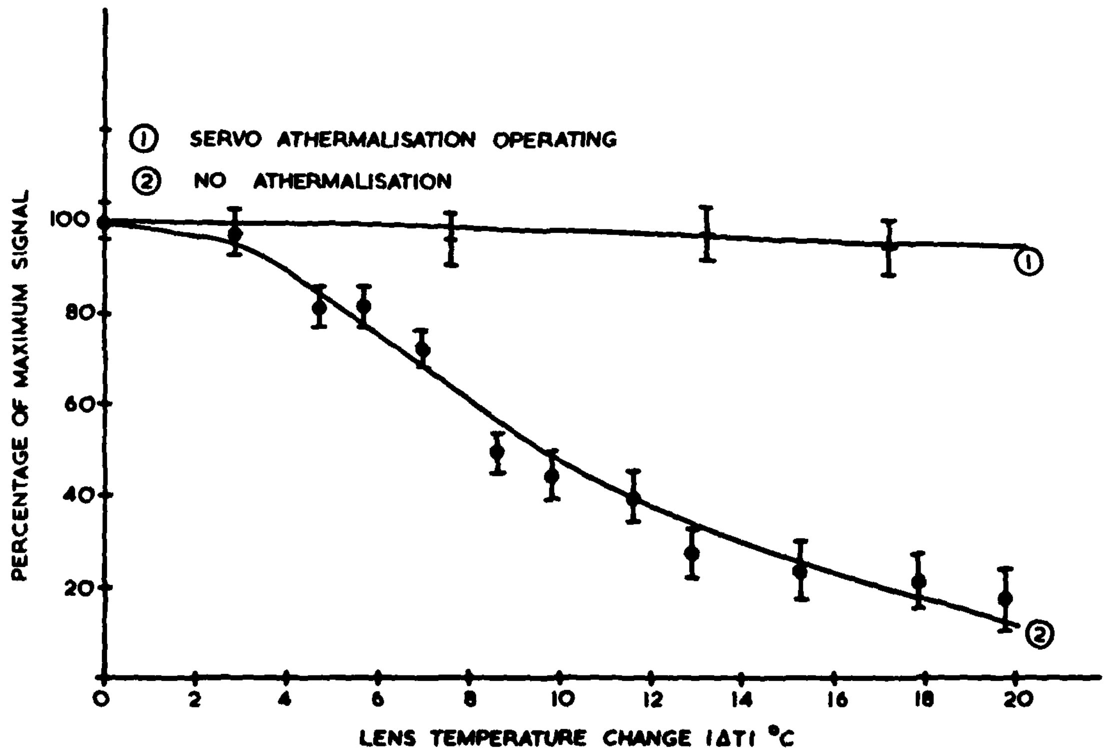

FIG.3 PERCENTAGE OF MAXIMUM SIGNAL AGAINST LENS TEMPERATURE CHANGE WITH AND WITHOUT ATHERMALISATION FOR THE 8-12μm WAVE BAND

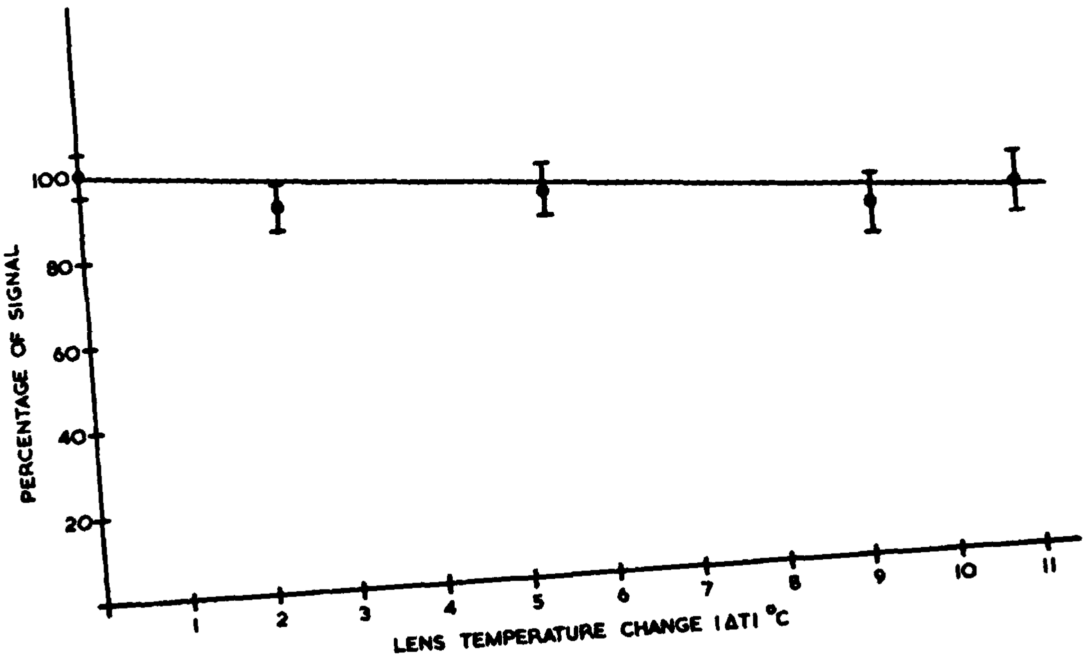

FIG. 4 PERCENTAGE OF MAXIMUM SIGNAL AGAINST LENS TEMPERATURE CHANGE FOR THE ATHERMALISATION SERVO OPERATING IN THE (3-5)µm WAVEBAND

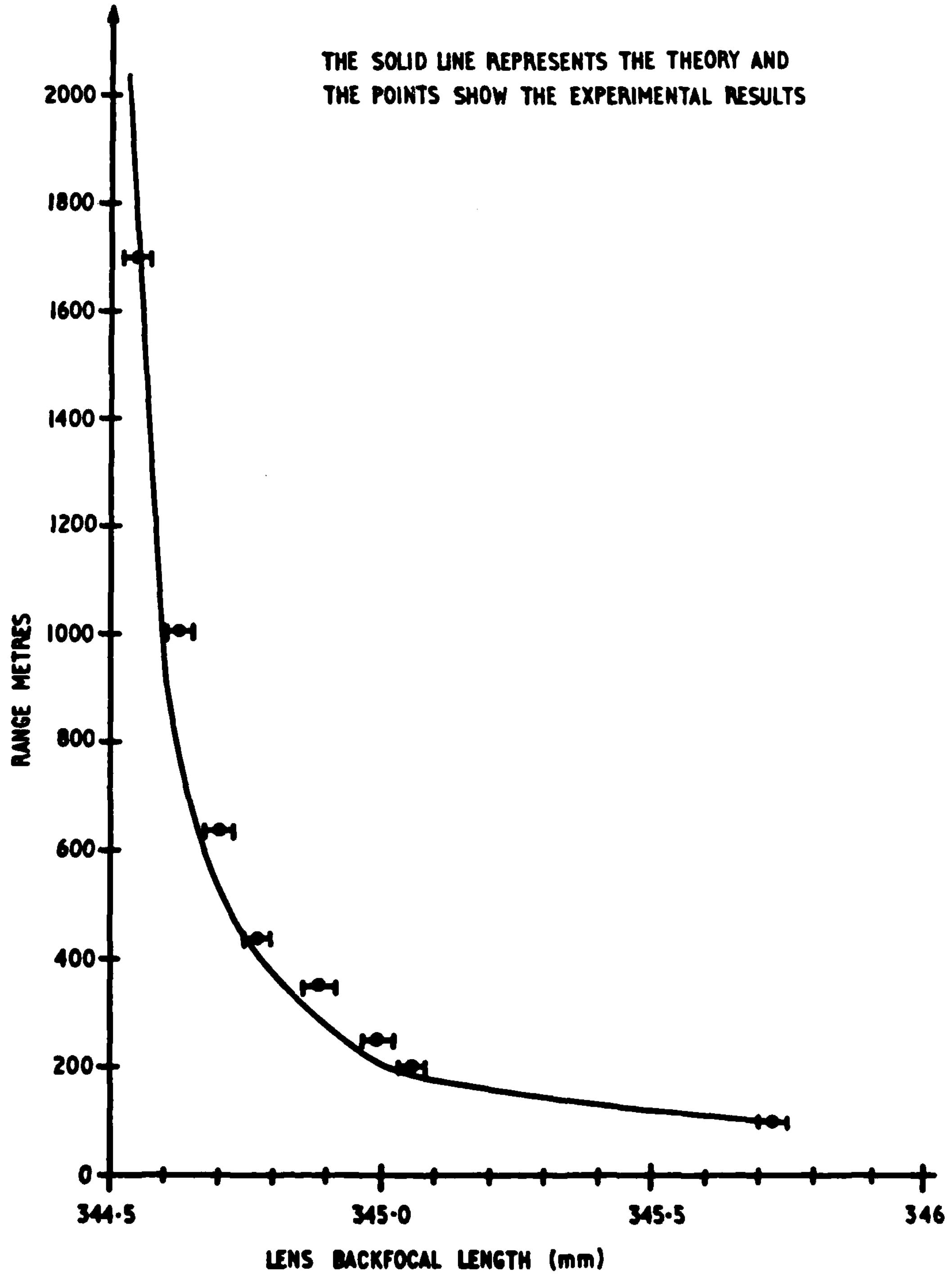

FIG.5 THEORETICAL AND EXPERIMENTAL BACKFOCAL LENGTH AS A FUNCTION OF RANGE

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